Biological Motion as an Intuitive and Inviting Non-Symbolic Communication to Improve Human Interaction with Autonomous Systems

Ruisi Shi[1,2], Jingyu Zhang[1,2*] , Yunqi Yang[3], Liang Zhang[1,2], Xianghong Sun[1,2], Yijing Zhang[4,5], Shanguang Chen[4,5,6],

1. CAS Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, Beijing, China.
2. Department of Psychology, University of Chinese Academy of Sciences, Beijing, China.
3. Department for General Psychology and Cognitive Neuroscience, Friedrich Schiller University Jena, Germany.
4. Department of Industrial Engineering, Tsinghua University, Beijing 100084, China
5. National Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Center, Beijing 100094, China
6. China Manned Space Program, Beijing 100080, China

*Correspondence author: Dr. Jingyu Zhang, zhangjingyu@psych.ac.cn

Abstract

In a future where autonomous systems are widespread in the real world, humans must be able to swiftly and accurately interpret the status and intentions of these systems in various contexts. However, existing symbolic-based interactions (such as language and icons) encounter difficulties in addressing the challenges of universality, comprehension, and visibility. This study provides a novel non-symbolic communication framework based on biological motion. Using this framework, we designed a new external human-machine interface (eHMI) to enhance pedestrian understanding and acceptance. Our findings suggest that biological-based eHMI significantly improves comprehension across diverse groups, including children and non-native speakers, enhancing decision-making in street-crossing scenarios and improving motion speed perception.

Introduction

Autonomous systems are poised to transform numerous aspects of daily life, with autonomous driving technology representing a particularly significant shift in the automotive industry. As these systems become more integrated into real-world environments, ensuring clear and effective communication between autonomous vehicles (AVs) and pedestrians becomes essential. Traditional driver-pedestrian interactions, which rely on non-verbal cues[1], are absent in AV operations, potentially

increasing accident risks and reducing public acceptance[2]. Research has thus focused on developing external human-machine interfaces (eHMIs) to express AV intentions and alleviate pedestrian uncertainty[3]. The user experience with eHMIs should be positive, fostering public trust and acceptance of AV technology[4].

Current eHMIs, primarily text and icon-based, have proven effective but remain limited in universal intuitiveness[5]. In fact, a multitude of existing eHMI design solutions lacks comprehensive understandability evaluations, making it difficult for users to grasp their meanings. This complexity hampers pedestrian adoption of diverse interface types, exacerbating comprehension difficulties and impeding interactions between autonomous vehicles and vulnerable road user groups[6]. There's a need for interfaces that are immediately understandable to all, including individuals with limited language skills or familiarity with local traffic conventions[2]. Icons and animations require users to have a pre-existing understanding of traffic symbols, which poses a challenge for children and non-natives. These groups particularly struggle with eHMI elements, with children at significant risk in traffic environments[7-9] and non-natives facing challenges due to cultural differences in symbolism and potential language barriers[10-13].

Furthermore, even well-designed eHMIs are limited by perceptual distance, affecting safety effectiveness. A substantial portion of situational awareness errors are due to perceptual mistakes[14], with recommendations suggesting at least 20 MOA visual angle for symbol and text legibility[15]. However, environmental factors can reduce visibility, emphasizing the need for adaptable eHMI solutions that cater to diverse environmental and user needs to enhance vehicle-pedestrian communication safety and efficiency.

In the pursuit of intuitive and universally comprehensible eHMI designs, biomimetic approaches offer innovative but challenging solutions. These designs aim to convey vehicle intentions through naturalistic cues, such as car hood feathers mimicking avian territorial behavior, signaling yielding or readiness to move[16,17]. However, the effectiveness of such designs is constrained by their alignment with human instinctual understanding, particularly when inspired by non-mammalian species with less relevance to human behavior.

The integration of various eHMI features holds promise for enhancing vehicle-pedestrian communication, but challenges remain. Behavioral cues borrowed from animal behaviors may not be intuitively understood by pedestrians due to a limited shared evolutionary history with humans. Moreover, the technical integration of dynamic biomimetic features into vehicle design can be complex and may require significant modifications[18]. These considerations emphasize the ongoing need for research and development in the field of biomimetic eHMI design, with the goal of facilitating intuitive and efficient pedestrian interactions with autonomous vehicles.

Non-verbal cues in animal social interactions, which are critical for conveying intentions and states, are products of evolutionary development and critical for survival, particularly in recognizing predators and conspecifics[19-21]. Johansson's pioneering research in the 1970s on biological motion using point-light displays (PLDs) revealed the human brain's adeptness at interpreting complex motion patterns

from simple visual cues such as isolated limb movements[22-24]. Moreover, dynamic PLDs, especially point-light walkers (PLWs), have been found to elicit greater visual system activation compared to their static counterparts, indicative of an evolutionarily tuned attentional mechanism[25].

In the domain of human-machine interaction, our research applies these principles to the development of intuitive vehicle-external communication systems. We focus on translating mammalian biological motion into easily understandable signals for pedestrians, aiming to unambiguously communicate pedestrian right-of-way and vehicle intentions. This method seeks to enhance the clarity of vehicle actions, thereby improving the safety and efficiency of human-machine interactions. Grounded in the evolutionary and biological salience of mammalian movements to human perception, our approach is further supported by the genetic and behavioral similarities between humans and other mammals, which could significantly enhance the efficacy of external human-machine interfaces (eHMIs) .

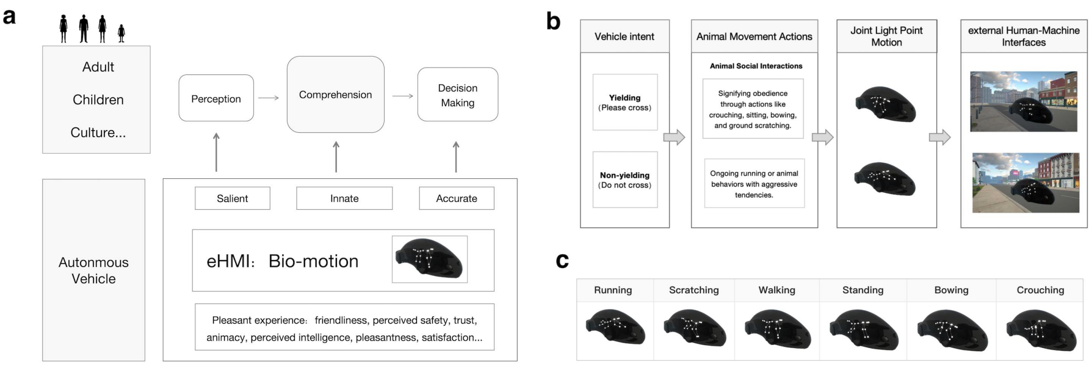

Figure 1: Human-Autonomous Vehicle Interaction through Bio-motion eHMI a. Overview of Interaction Process: Illustrates the dynamic communication loop between various pedestrian groups and autonomous vehicles, including the key roles of perception, comprehension, and decision-making. b. Bio-motion eHMI Conceptualization: the innovative eHMI design that employs bio-mimetic motion to express vehicle intentions. Using animalistic movement patterns, rooted in the innate understanding of biological cues, to signal vehicle behavior to pedestrians. c. Bio-motion eHMI Elements: a suite of bio-mimetic signals, each representing specific autonomous vehicle actions. These include running (keep moving), scratching (decelerating), walking (initiating movement), standing (stationary), bowing (invitation to proceed), and crouching (waiting), all designed to convey operational states and intentions to pedestrians using universally recognizable gestures.

We present a novel approach to vehicular communication by employing Point Light Displays (PLDs) that replicate mammalian movements, translating the vehicle's operational state and intentions into a biomimetic, user-centric format. Such PLDs can symbolize a vehicle's autonomous status or dynamism—acceleration or deceleration—through analogous actions such as running or grazing, thereby facilitating pedestrians' accurate prediction of autonomous vehicle behaviors[26-28]. Moreover, vehicle intents, such as pedestrian detection and forthcoming maneuvers

like yielding, are illustrated by activities akin to walking or standing, which have been shown to significantly enhance the efficacy of interactions[27,29]. Pedestrian instructions, including whether to cross or not, can be intimated through gestures such as crouching or bowing, shifting focus from vehicle actions to pedestrian guidance[30]. This biomimetic design aims to intuitively impart critical external human-machine interface (eHMI) information, paralleling familiar animal behaviors to improve the effectiveness and safety of vehicle-pedestrian exchanges.

We believe this new design embodies three important features: an innate and universal understanding, high recognizability, and the ability to induce pleasant and heart-touching interactions. First, the proposed design capitalizes on the innate and universal understanding of biological motion, a capability evident from infancy and consistent across cultures. Neonates demonstrate a preference for biological motion within days of birth, a proclivity that continues to develop robustly throughout early childhood and remains resilient into later life, even among those with visual impairments[31-36]. Research confirms the cross-cultural universality of this ability, presenting it as an ideal, globally comprehensible medium for external human-machine interfaces (eHMI)[37].

In terms of recognizability, point-light displays (PLDs) adeptly convey biological motion, facilitating rapid recognition even at substantial distances or under visually challenging conditions[22,38-40]. The visual system's perceptual sensitivity to PLD-based biological motion is maintained regardless of contrast or spatial frequency, underscoring its effectiveness in various environmental contexts, including low light or cluttered backgrounds[24,41]. This resilience makes PLD-based biological motion a versatile and reliable eHMI medium, crucial for safety and efficiency where quick and accurate signal recognition is essential.

Furthermore, the design fosters pleasant and emotionally resonant interactions. Interactions with biological motions, akin to those with animals, are inherently joyful and have a positive impact on mental health[42]. This biophilic orientation is genetically ingrained, facilitating a connection with the natural world and improving acceptance of autonomous vehicles. By incorporating biological motion into eHMI, pedestrians engage with a familiar visual language that diminishes detachment and unfamiliarity with autonomous vehicles, enhancing the human-computer interaction experience. This biologically intuitive communication method resonates with Licklider's vision of a symbiotic relationship between humans and technology, augmenting human experiences rather than creating a divide[31]. This innovative eHMI approach promises to not only heighten road safety but also enrich the human experience amidst the rise of autonomous vehicles.

Result

Comprehension of Bio-motion Interactions

a. Among Chinese Adults (concept test)

We observed bio-motion induced better understanding in vehicle movement than both text and non-display ($ps < .001$). In understanding vehicle intent, bio-motion performed at the same level as compared to text-eHMI ($p > .05$), both of which outperformed non-display significantly ($ps < .001$).

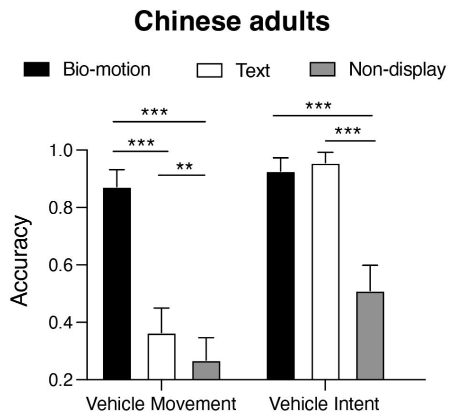

Figure 1. Comparison of 3 types of eHMIs in Objective Accuracy Rates. A total of 32 Chinese adults were recruited in this study

b. Among children

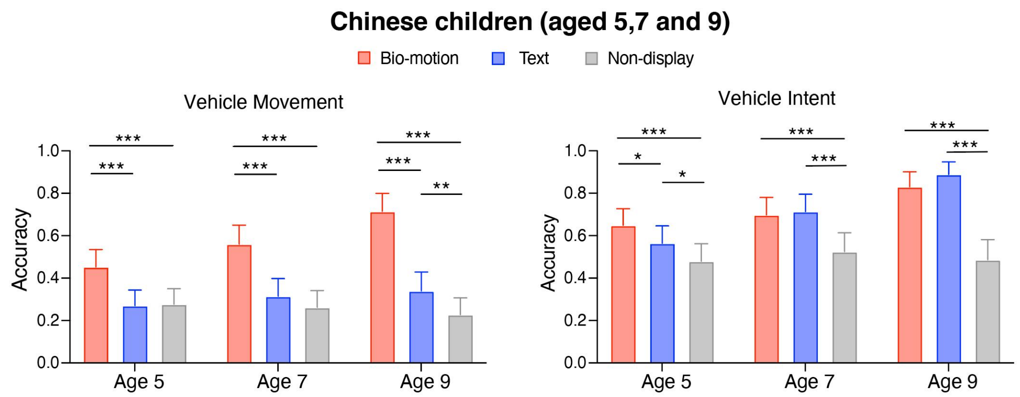

Figure 2. Accuracy of judgement of vehicle movement and intent. This study involved a cohort of 96 children, divided into three age groups: 37 children aged five, 31 children aged seven, and 28 children aged nine.

For 5-year-olds, Bio-motion induced higher understanding in both vehicle movement and intent than both Text and Non-display ($ps < .05$) . For 7 and 9-year-olds, bio-motion induced greater accuracy in vehicle movement than both other two eHMIs ($p < .001$), and induced greater accuracy in understanding vehicle intent than Non-displays ($p < .001$). Text eHMI has advantages in promoting the understanding of vehicle intent for both 7 and 9-year-olds ($ps < .001$), and promoting the understanding of vehicle movement for 9-year-olds ($ps < .01$).

c. Among Chinese and German Individuals

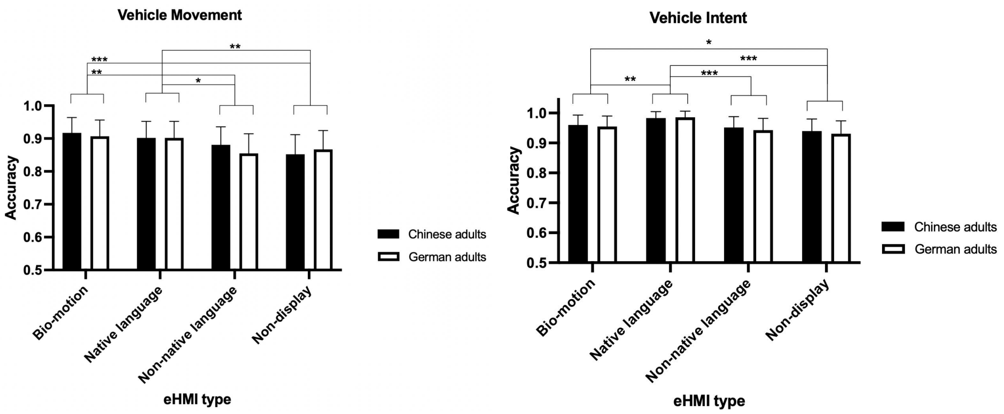

Figure 3. Comparative Efficacy of Four eHMI Types on Objective Accuracy Rates in Interpreting Vehicle Movement and Intent by Chinese and German Participants. The study sampled 70 individuals, evenly divided with 35 German and 35 Chinese participants. We accounted for subject variability using a generalized mixed-effects model to analyze the Objective Accuracy Rate of vehicle behaviors, which includes vehicle movement and intent. The interaction effect of country and eHMI type was not significant, nor was the main effect of country. The main effect of eHMI type was significant ($p < .01$).

We found bio-motion eHMI resulted in universal advantage in understanding vehicle movement across both Chinese and German participants ($p < .001$); it outperformed non-native language eHMI and non-display (both $p < .01$).

In conveying the vehicle intent, native language eHMI performed the best (average comprehension rates were 98.3% among Chinese participants and 98.6% among German participants, $p < .01$), but bio-motion eHMI also resulted in near-perfect understanding (96.0% for Chinese and 95.5% for German participants) and significantly outperformed non-display eHMI ($p < .05$), while non-native language eHMI had no significant difference with non-display eHMI ($p > .05$).

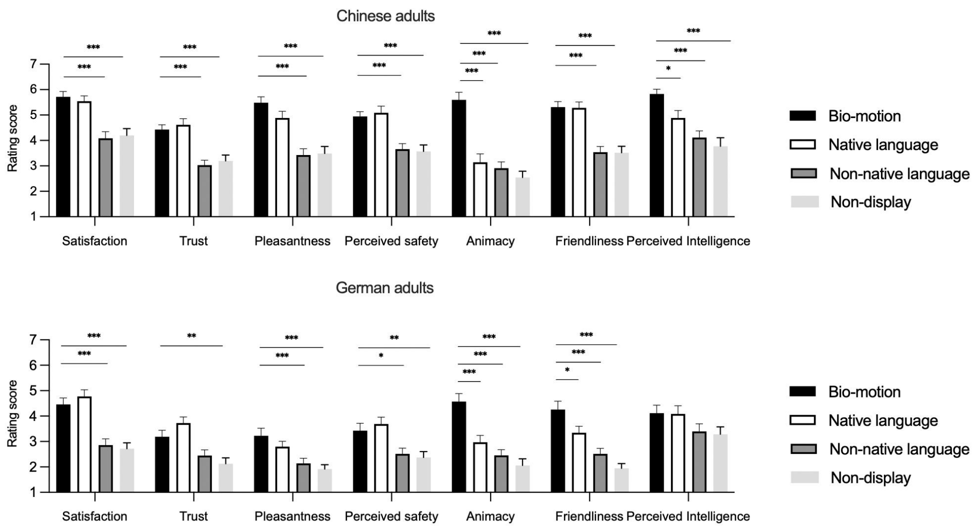

Figure 4. The bar chart represents the impact of different types of external Human-Machine Interaction systems (eHMI) on Chinese and German participants' satisfaction, trust, pleasantness, perceived safety, animacy, friendliness and perceived intelligence.

$^{***}p< 0.001$, $^{**}p< 0.01$, $^{*}p< 0.05$

For the bio-motion eHMI, both Chinese and German participants demonstrated a consistent advantage over non-native language and no-display conditions in terms of satisfaction, trust, pleasantness, and perceived safety, with all measures significantly exceeding those conditions ($p < .05$). In the dimension of animacy, bio-motion eHMI showed a definitive superiority among participants from both countries ($p < .001$). Regarding friendliness, an advantage was observed among German participants ($p < .05$), while perceived intelligence was notably higher among Chinese participants ($p < .05$).

The Impact of Bio-motion eHMI on Street-Crossing Decisions

a. Among children

In non-yielding Scenarios, bio-motion eHMI and native language eHMI significantly reduced children's sense of safety when crossing the street at close distances. For 5-year-olds, this effect was significant only within the nearest 10 meters to pedestrians ($p = 0.007$), while for children aged 7 and 9, the effect extended to a distance range of 10-20 meters (7 years: $p < 0.01$; 9 years: $p < .05$). Across all age groups, there was no significant difference between bio-motion eHMI and native language eHMI.

In yielding scenarios, 5-year-old children showed a significant decrease in safety perception within a distance of 5 to 10 meters when responding to native language eHMI ($p = 0.048$), whereas there was no significant difference under bio-motion eHMI and non-display conditions. In contrast, children aged 7 and 9 showed no significant difference in response to all types of eHMI ($ps > 0.05$).

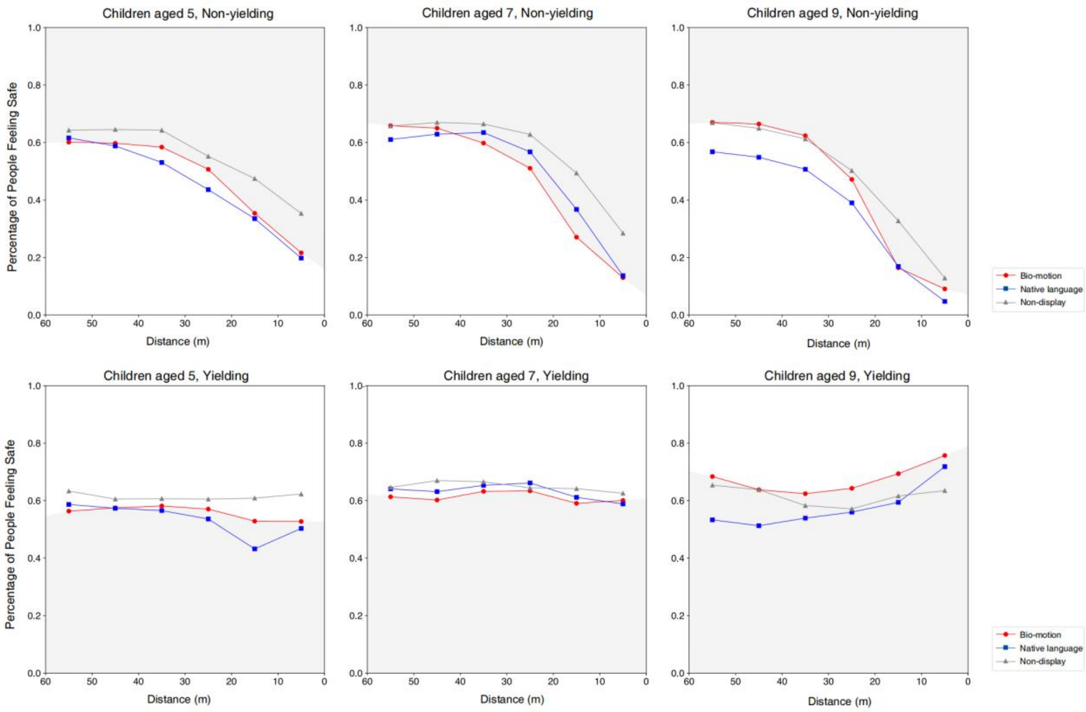

Figure 5. the percentage of Children (aged 5, 7 and 9) feeling safe to cross in vehicle yielding and non-yielding scenarios under 3 eHMI conditions (Bio-motion eHMI, Native language, Non-display). In yielding situations, improved eHMI correlates with an elevated safety perception, represented by the shaded region above the line (specifically bio-motion eHMI as depicted here). Conversely, in non-yielding situations, enhanced eHMI corresponds to a decreased safety perception, indicated by the shaded area below the line.

b. Among Chinese and German Individuals

In non-yielding scenarios, we examined how Chinese and German individuals respond to various eHMI types when deciding to cross the street. For Chinese individuals, bio-motion eHMI significantly reduced perceived crossing safety compared to native language eHMI and non-display from 10 to 30 meters (with significant differences in the 10-20 and 20-30 meter ranges: $p < 0.001$ and $p < 0.01$, respectively). A notable difference between native language eHMI and non-display was observed in the 10-20 meter range ($p = 0.011$). For Germans, bio-motion eHMI substantially decreased perceived safety over a 10 to 50 meter range, showing consistent significance across this span compared to non-native language eHMI and non-display (*ps* < .05 for 10-50 meters).

In yielding scenarios, native language eHMI notably increased perceived safety for Chinese and German individuals crossing within a 5-30 meter range, outperforming bio-motion eHMI and non-display ($p < .01$). For German participants, bio-motion eHMI markedly improved perceived safety from 5 to 40 meters, offering a significant benefit over non-native language eHMI and non-display (*ps* <.05).

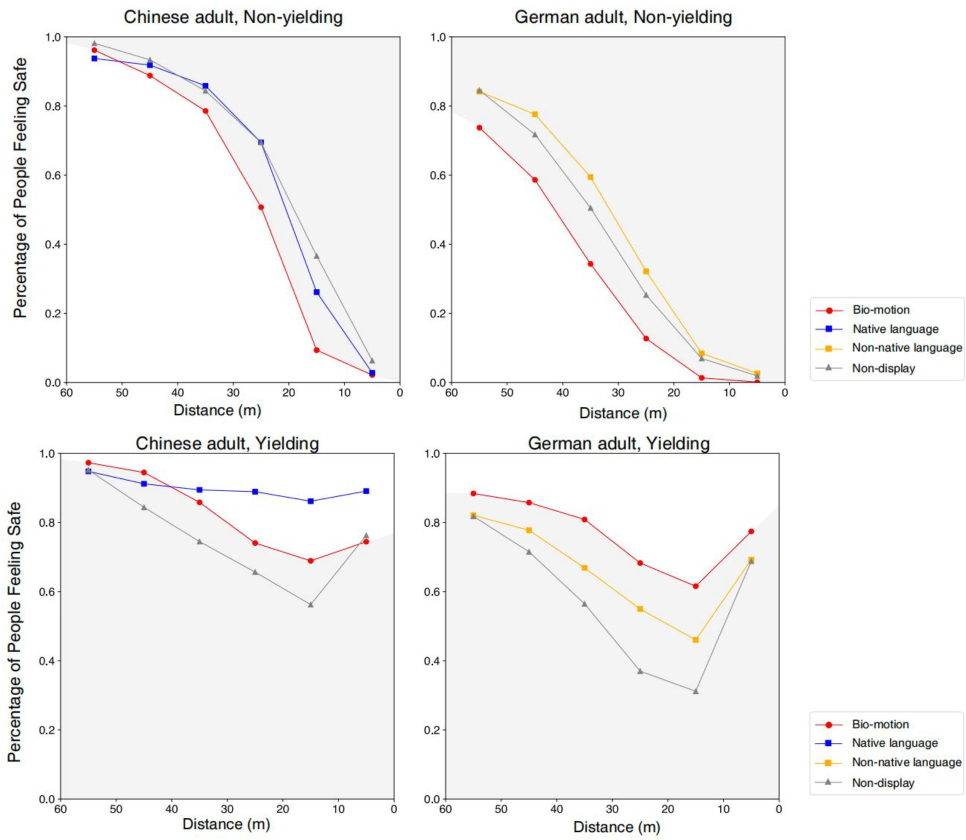

Figure 6. the percentage of Chinese and German participants feeling safe to cross in vehicle yielding and non-yielding scenarios under different eHMI conditions (Bio-motion eHMI, Native language, Non-native language, Non-display). In yielding situations, improved eHMI correlates with an elevated safety perception, represented by the shaded region above the line (specifically bio-motion eHMI as depicted here). Conversely, in non-yielding situations, enhanced eHMI corresponds to a decreased safety perception, indicated by the shaded area below the line.

Motion Speed Change Detection at Various Distance Among Chinese Adults

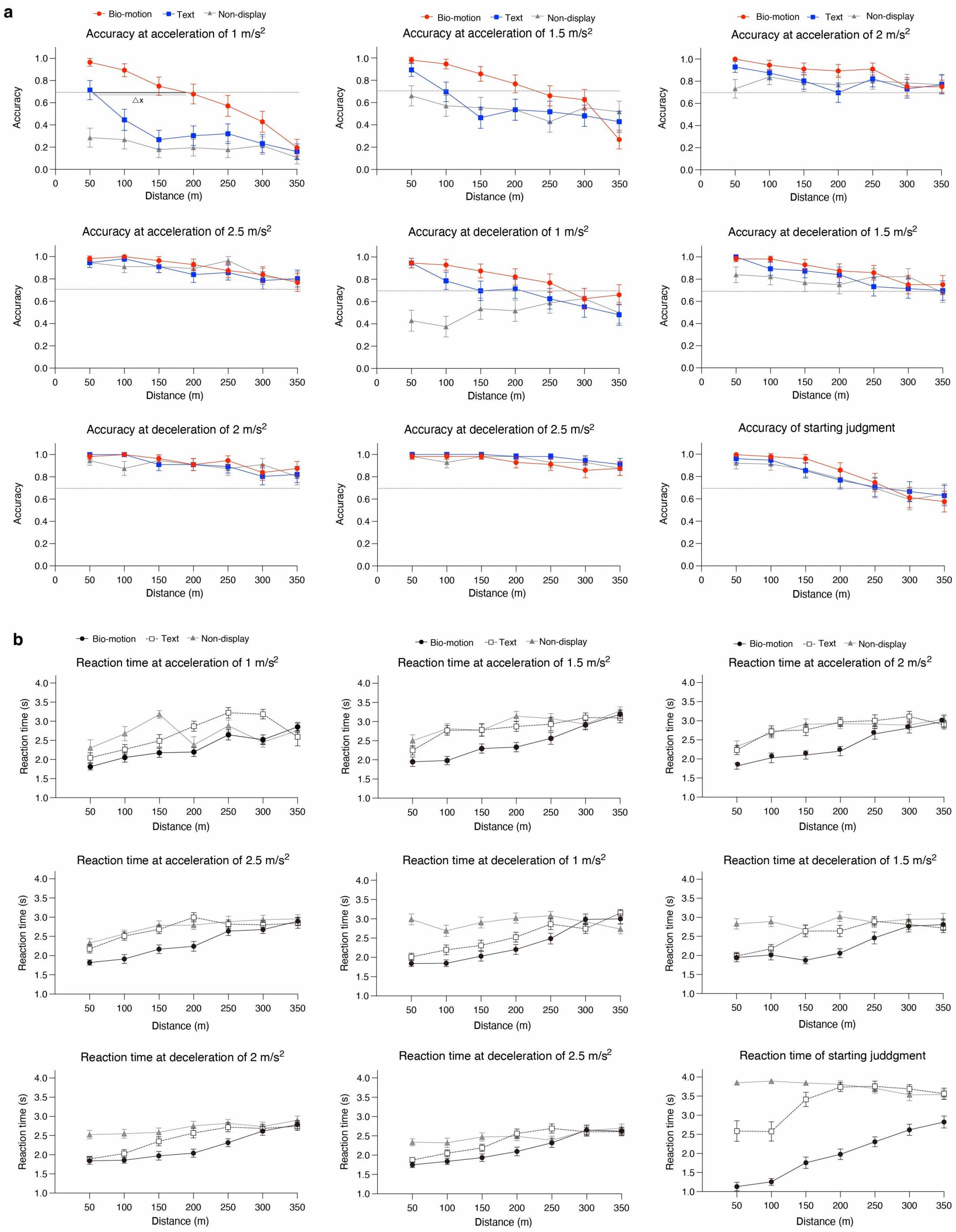

Figure 7. Objective Accuracy Rates and Reaction Times Across Three eHMI Types (bio-motion eHMI,text eHMI and non-display) (a) Accuracy of acceleration, deceleration and starting judgement; (b) Reaction time of acceleration, deceleration and starting judgement

For acceleration conditions, we observed the accuracy of all three eHMIs gradually decreased with increasing distances while the response time increased as distance increased. More specifically, when the acceleration was 1 m/s², Bio-motion eHMI was superior to Text eHMI and Non-display in aspect of both accuracy ($p < .01$) and response time ($p < .001$) at a perceptual distance of 200 m; Bio-motion eHMI was superior to Text eHMI and Non-display in aspect of only accuracy ($p < .001$) at 100m and 150m; Bio-motion eHMI was superior to Text eHMI for only

response time at 250m ($p < .01$) and 300m ($p < .001$). Notably, at a 70% level, the accuracy of Bio-motion eHMI at 200m was equivalent to that of the Text eHMI at 50m. Similarly, when the acceleration was 1.5 m/s^2, Bio-motion eHMI was superior to Text eHMI and Non-display in aspect of both accuracy ($p < .05$) and response time ($p < .05$) at a perceptual distance of 150 m; Bio-motion eHMI was superior to Text eHMI and Non-display in aspect of only response time ($p < .01$) at 100m and 200m. Moreover, when the acceleration was 2 m/s^2, Bio-motion eHMI was significantly superior to Text eHMI and Non-display ($p < .001$) in aspect of only response time at perceptual distances of 100m, 150m, and 200m. Also, when the acceleration was 2.5 m/s^2, Bio-motion eHMI was significantly superior to Text eHMI and Non-display ($p < .01$) in aspect of only response time at perceptual distances of 100m, 150m, and 200m. Overall, at a 70% accuracy rate, bio-motion eHMI enhanced the visual distance by an additional 100 plus meters relative to text eHMI, further demonstrating its 'zoom-in' effect (See Supplementary Material). The study's analysis highlights bio-motion eHMI's pervasive advantage across various distances and acceleration rates, underscoring its robust performance in acceleration judgment. As distance increases and acceleration rates rise, the superiority of bio-motion eHMI slightly diminishes, indicating a dependency on external cues which become sparse with greater speed and distance.

For deceleration conditions, we observed the accuracy of all three eHMIs gradually decreased with increasing distances while the response time increased as distance increased. Notably, at a 70% level, the accuracy of Bio-motion eHMI at 250m was equivalent to that of the Text eHMI at 200m. More specifically, when deceleration was -1.5 m/s^2, Bio-motion eHMI significantly outperformed Text eHMI in aspect of accuracy ($p < .01$) as an overall main effect and in aspect of response time ($p < .01$) particularly at distances of 150m and 200m. Also, when deceleration was -2 m/s^2 and -2.5 m/s^2, Bio-motion eHMI significantly outperformed Text eHMI in aspect of response time ($p < .01$) at distances of 200m.

For vehicular starting scenarios, we also observed the accuracy of all three eHMIs gradually decreased with increasing distances. And Both Bio-motion and Text eHMI reaction times escalated with distance, while the Non-display condition consistently maintained a higher level. Notably, at a 70% level, the accuracy of Bio-motion eHMI at 200m was equivalent to that of the Text eHMI at 50m. Moreover, Bio-motion eHMI significantly outperformed Text eHMI in aspect of response time ($p < .05$) at distances between 50m to 350m. At a 70%-80% accuracy rate, bio-motion eHMI extended the visual distance by 10.33~44.55m compared to text eHMI, effectively achieving a 'zoom-in' effect (See Supplementary Material).

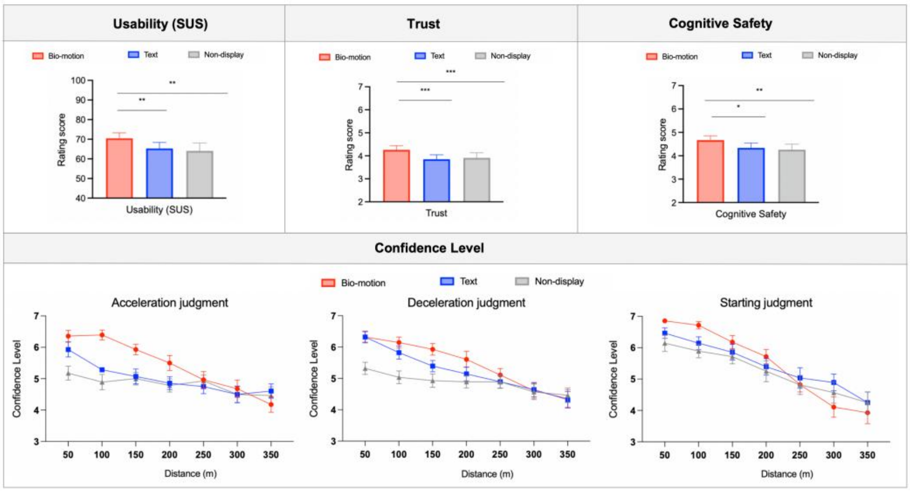

Figure 8. Comparative Subjective Ratings of Usability, Trust, Cognitive Safety, and Confidence Across 3 eHMI Types in perception stage. Subjective assessments revealed Bio-motion eHMI as superior in Usability compared to Text eHMI and Non-display, indicating no significant distinction between Text eHMI and Non-display. Trust ratings were also higher for Bio-motion eHMI against both Text eHMI and Non-display. In terms of Cognitive Safety, Bio-motion eHMI outshined Text eHMI and Non-display. Confidence in acceleration judgement with Bio-motion eHMI significantly exceeded that of Non-display at both 50m and 150m distances, and was notably higher than both Text eHMI and Non-display at 100m. For deceleration, Bio-motion eHMI's confidence ratings consistently surpassed Non-display at 50m, 100m, and 150m. Across vehicular starting scenarios, confidence levels decreased with distance for all eHMI types, showing no significant variance.

Discussion

Our study introduces a novel method using biological kinematics, particularly leopard movements, to develop an advanced external Human-Machine Interface (eHMI) for vehicular-pedestrian communication. This bio-motion eHMI represents a significant fusion of biology and technology, setting a foundation for future research in this area.

In the comprehension phase, bio-inspired eHMIs significantly enhanced vehicular motion and intent understanding among Chinese adults, outperforming text-based eHMIs or no display. Study 1 suggests this is due to an innate ability to recognize biological movement[42,43], crucial in zoological social dynamics. This bio-motion recognition advantage appears universal, aiding even five-year-olds in vehicle behavior understanding, as evidenced in Study 2. Preschoolers showed better movement comprehension with bio-motion eHMI, possibly due to its simplicity and inherent neural processes[44,45]. The understanding of vehicle intent via eHMI varies with age; seven and nine-year-olds understood vehicle intent with text eHMI as well as bio-motion eHMI, unlike five-year-olds, possibly due to language development[46] while understanding of bio-motion eHMI seems age-independent, likely because of early exposure to biological movements and learning through observation[47]. Study 3

confirmed bio-motion eHMI's cross-cultural effectiveness, showing no significant comprehension difference between Chinese and German adults. Despite language-specific eHMIs' benefits, bio-motion eHMI's effectiveness implies its global applicability. It also improved subjective experience, surpassing other eHMI types in satisfaction, trust, cognitive safety, and perceived intelligence, particularly against non-native language eHMIs and no display, possibly due to an innate neonatal attraction to bio-motion displays[31], a result of evolutionary developments in human vision.

In our supplementary study, we assessed whether upright, complete bio-motion eHMI with biomimetic and dynamic cues enhances understanding compared to scrambled or inversed light point displays. Bio-motion eHMI significantly outperformed both Inverted eHMI ($p < .001$) and Scrambled eHMI ($p < .001$) in vehicle movement and intent comprehension, meaning the global biomimetic entity information embedded in bio-motion plays critical role in vehicle understanding on top of local dynamic cues. This aligns with the findings of Troje and Westhoff [48] as well as Farah et al.[49], who noted decreased recognition accuracy with inverted bio-motion or facial-pattern interference. This improvement likely stems from a human preference for biomimetic entities, as shown in infants' attraction to face-like stimuli[45,50], indicating the importance of bio-motion's biomimetic and dynamic qualities in understanding vehicle movements.

In the decision-making stage, study 4 found that among Chinese participants, Bio-motion eHMI equaled text displays in yielding scenarios and surpassed no display conditions in decision-making, enhancing vehicle intention understanding and pedestrian safety. This effectiveness transcends cultural barriers, as both Chinese and German adults found Bio-motion eHMI effective in pedestrian crossings. In yielding situations, adults from both cultures felt safer with Bio-motion eHMI than no display. However, in non-yielding scenarios, Bio-motion eHMI reduced perceived safety, potentially serving as a vital danger cue and thereby increasing pedestrian safety. This cross-cultural efficacy underscores Bio-motion eHMI's potential for global use in improving safety perceptions, even in non-native language environments. Study 5 investigated Bio-motion eHMI's impact on different age groups and traffic conditions. In yielding scenarios, 9-year-olds felt significantly safer with Bio-motion eHMI compared to native-language eHMI or no display, boosting their subjective safety. Conversely, in non-yielding scenarios, it reduced perceived safety among 7-year-olds more than other displays, indicating its effectiveness in alerting children to danger. This aligns with McLeod's findings[51] on developmental milestones around 7-8 years, where children become more aware of environmental threats. The results for 5-year-olds were less typical, possibly due to their less intuitive understanding of video-based tasks. Overall, Bio-motion eHMI's effectiveness varies with age and scenario, suggesting its potential for contextual adjustment in safety perception. These findings are vital for future Bio-motion eHMI applications in traffic safety.

In our perception stage study, Bio-motion eHMI demonstrated superior accuracy and quicker response in motion speed change judgment than Text eHMI and Non-display. More specifically, it excelled in acceleration accuracy judgments

between 100m and 200m and shows quicker reactions in acceleration, deceleration, and onset judgments compared to alternatives. This underlines Bio-motion eHMI's perceptual task dominance over Text or icon-based eHMIs, complementing Rettenmaier's findings[52] on icon-based eHMI's greater recognition distance over Text eHMI.

Our findings also suggest humans are less accurate in judging acceleration than deceleration, highlighting potential safety concerns. Bio-motion eHMI's advantage in acceleration perception likely stems from familiarity with biological motion patterns, consistent with Tremoulet & Feldman[53] and Pennycuick[54]. These patterns, recognized through memory theories like the Direct Access Model and Dual Coding Theory[55,56], enhance quick recall and evaluation. In contrast, unfamiliar forms like Text eHMI slow judgment processes. Thus, Bio-motion eHMI's familiarity offers a perceptual edge in vehicle movement comprehension, outperforming other eHMI types in speed and accuracy.

This study demonstrates Bio-motion eHMI's effectiveness in improving pedestrian judgment and understanding of vehicle movements. Its rich social cues, like body orientation and gaze, could enhance communication in multi-user scenarios, increasing road-friendliness. However, its attention-grabbing nature may cause visual crowding, posing a risk in complex environments. Future research should prioritize ecological validity, employing Virtual Reality (VR) to simulate real-world scenarios. These experiments would test Bio-motion eHMI's adaptability in varied road conditions (especially in crowded urban areas), involving pedestrians, vehicles, bicycles, visual distractions; under different environmental noises, such as different weather and lighting conditions; and across various road types like highways, urban streets, and rural roads. This approach is vital for understanding its effectiveness in challenging contexts and guiding its optimization.

Conclusively, the bio-motion eHMI not only demonstrates efficacy in singular cultural contexts but also exhibits a degree of cultural universality, with the potential to swiftly modify pedestrians' safety perception in non-yielding scenarios, providing robust theoretical backing for the global implementation of this technology. The study highlights its varied effectiveness across age groups and scenarios, especially in contextually adapting safety perceptions, providing important implications for traffic safety initiatives.

Method

Comprehension of Bio-motion Interactions Among Chinese Adults

In study 1,we conducted a concept test to assess how the bio-motion eHMI form might surpass the most effective eHMI (text-based)[57] and non-display condition among Chinese adults. The biomimetic point-light model used in this experiment is informed by the cheetah in nature. The cheetah's skeletal structure and movement patterns were studied, and a cheetah motion skeleton model was created in the 3D

computer graphics software, Blender. Key light points that best represent the cheetah's form were identified. Following adjustments to the cheetah skeleton model's biomimetic motion in Blender, the model was imported into the game engine Unity for material rendering of the biomimetic point lights and to link preset actions of the cheetah skeleton model, ultimately achieving the production of the experimental scenario.

The cheetah serves as our biomimetic model due to its exceptional skeletal movement characteristics and biomechanical features, which mirror ideal vehicle movement. Cheetahs display locomotive prowess and high-speed stability, underpinned by their robust iliopsoas muscles that facilitate pitch stability during rapid acceleration and counteract pitch torque around the hip joint[58]. Their lumbar vertebrae's flexibility augments propulsion in high-speed runs, indicating superior stability and acceleration capacity. Furthermore, skeletal features like an elongated pelvis, wide scapula motion range, and lengthy metacarpals and metatarsals allow swift leg motion and significant torque output, essential for understanding vehicle motion states[59-61].

In our study, we constructed a comprehensive set of Basic Action Elements that comprises numerous spot movements such as running, walking, standing, squatting, sitting, looking around, shaking the head, bowing, and pawing the ground. These elements were intricately combined to create a suite of dynamic animations, to effectively depict vehicle motion.

We source these action elements from observations of a cheetah's real-life movements. In addition, our research distinguishes between the sequences of movements for a vehicle in motion and one that is stationary. This differentiation allows us to mimic various scenarios of vehicle interaction with pedestrians, further enhancing the understanding and communication between autonomous vehicles and humans. For example, ***Yielding:*** The sequence of spot movements includes slowing down from a run, pawing the ground, standing, bowing, squatting, and sitting. This sequence mimics a car giving way to pedestrians during transit, drawing parallels with a real-life scenario where a cheetah, running at high speed, spots an obstacle and needs to stop urgently. This scene integrates actions such as high-speed running, looking around while running, slow running, and pawing the ground. To make the biomimetic cheetah more sociable and understandable to pedestrians, we also incorporate a human-like bowing action as a part of the series of biological motion patterns embedded within the vehicle's light points (See Figure 1). Supplementary videos illustrating the sequence of biomimetic light point movements are available in the supplementary material.

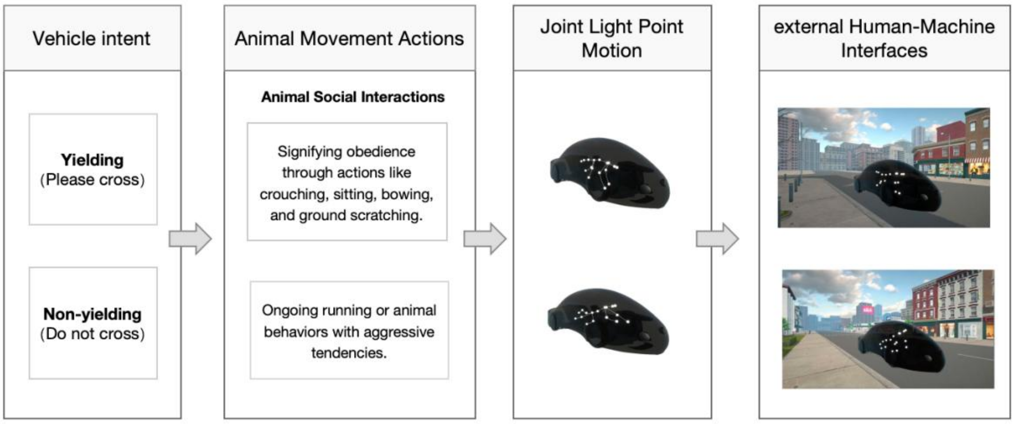

Figure 1. the design of bio-motion eHMI incorporating animal social interactions to convey vehicle intent and movements

Prior to the commencement of the experiment, participants were provided with an overview of the study context which revolved around comprehending the behavior of autonomous vehicles. Upon accessing the experiment via an online link, they were presented with a series of video clips illustrating different vehicular movements communicated through various interaction modalities. Each video clip was followed by a comprehension task where participants were required to answer two multiple-choice questions regarding their understanding of the vehicle's movement and the vehicle's intent, respectively. Specifically, they were asked, 'Based on the scene just shown, the vehicle's movement was ___,' with options: (A) From stationary to moving, (B) From moving to stationary, (C) Remaining stationary throughout, (D) Remain moving throughout. Another question was, 'What is the car attempting to communicate to you?' with responses: (A) Please cross, (B) Do not cross.

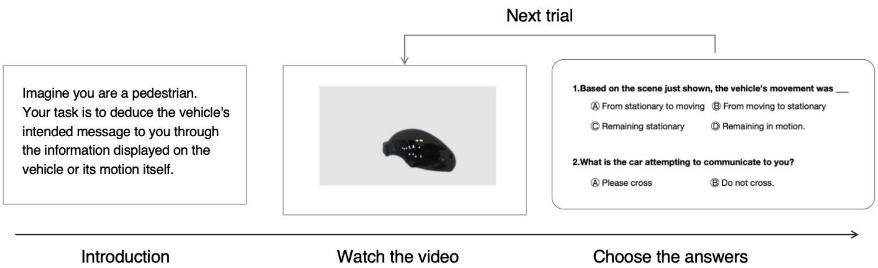

Figure 2. Flowchart depicting the experimental procedure where participants, as pedestrians, watch a video of a vehicle's movement and then answer multiple-choice questions to deduce the vehicle's intent and action.

Bio-motion Text Non-display

Figure 3. 3 different types of eHMI (from left to right: bio-motion eHMI, text eHMI, and non-display). (the same experimental materials for study 1 and 2).

Comprehension of Biological Motion Interaction: A Comparative Study of Children

Building on the outcomes from Experiment 1, our findings reveal that Bio-motion eHMI significantly surpasses Text eHMI and Non-display conditions in comprehending vehicular behaviors. To further corroborate these initial results, Study 2 is dedicated to examining the impact of Bio-motion eHMI, specifically on children's understanding.

Similar to the experimental materials and procedure in Experiment 1. Upon accessing the provided online link, participants were presented with a sequence of video clips. Subsequent to each video, they engaged in a comprehension task. This task prompted participants to answer two multiple-choice questions probing their grasp on the vehicle's movement and intent. Furthermore, participants were asked to identify which among the three eHMI types they found most intuitive for discerning the said vehicle dynamics.

These videos encompassed different interaction scenarios (e.g., starting without yielding, starting with yielding, moving without yielding, moving with yielding). Each scenario was randomized to appear twice in different road contexts. Therefore, throughout the three blocks, children observed a total of 24 video clips, culminating in an approximate experiment duration of 30 minutes.

Comprehension of Biological Motion Interaction: A Comparative Study of Chinese and German Individual

Building upon the initial concept tests, Experiment 3 explored the universal applicability of bio-motion eHMI across diverse cultural contexts. We assessed the comprehension of both Chinese and German participants regarding the vehicle's movement and intent via bio-motion eHMI, anticipating that their understanding would not only rival that of native-language eHMIs but also significantly exceed non-native language and non-display options. We manipulated the background stimuli from a simplified environment featuring a solitary target vehicle and minimal background distractions to a more intricate, realistic setting. This includes diverse distractive stimuli, varied vehicle flow, and complex traffic scenarios, subtly emulating the multifaceted nature of real-world conditions.

Similar to the experimental procedure in Experiment 1, participants from both China and Germany undertook the same tasks. Participants viewed a series of video clips. Each video was followed by a comprehension task, where participants responded to two multiple-choice questions related to their understanding of the vehicle's movement and intent. Subsequent to each task, participants assessed their response confidence and their subjective ratings.

Perceived Comprehensibility was measured using statements such as 'I feel that I can easily understand what the car wants to convey' and 'I feel that the way the car expresses itself is lively'. Responses were gathered on a 7-point Likert scale, with 1 representing 'strongly disagree' and 7 representing 'strongly agree' [62]. Following the questions related to a specific eHMI type, participants evaluated the respective eHMI

using various subjective measures, including Satisfaction, Trust [63], Cognitive Safety [64], Animacy, Perceived Intelligence, Perceived Safety[62], Pleasantness, and Friendliness[65]. For instance, Cognitive Safety was evaluated through statements such as 'I think the risk of this design of autonomous driving car is acceptable', while Animacy was assessed through responses to prompts like 'I feel this type of vehicle is as if it's alive', and so on. All these constructs were measured using validated scales with a Cronbach's alpha exceeding 0.8.

Bio-motion eHMI　　Chinese text eHMI　　German text eHMI　　Non-display

Figure 4. 4 different types of eHMI materials used for both Chinese and German (from left to right: bio-motion eHMI, Chinese text eHMI, German text eHMI and non-display).

The aforementioned sequence was repeated across 4 blocks corresponding to the four eHMI conditions. These were counterbalanced using a Latin square design to avert order effects. Each block consisted of 12 video clips, each paired with a comprehension question set and subjective assessments, making up a total of 48 test groups. Finally, participants shared basic demographic information and their driving experience.

The Impact of Bio-motion eHMI on Children's Street-Crossing Decisions

Studies 4 and 5 investigated the influence of bio-motion eHMI on street-crossing decision across various cultural backgrounds and among young children. Study 4 examined how bio-motion eHMI might enhance children's understanding of vehicular behaviors more effectively than native-language text and non-display conditions, thereby promoting safer street-crossing decisions. Study 5 assessed the broader impact of bio-motion eHMI on pedestrian street-crossing choices, focusing on its cultural universality and expected parity with native-language eHMI.

Figure 5. Overhead View of Unity Environment Scene (Red traces represent vehicle trajectories in non-yielding scenarios, red for yielding scenarios, and blue markers indicate pedestrian locations).

In study 4, Participants observed moving vehicles in a video of a Unity-based virtual environment that simulates real-world road conditions (See Fig). Vehicle parameters and biomotion scripts were aligned such that stride frequency and length

corresponded with the vehicle's speed and acceleration. In the yielding scenario, as the vehicle began to decelerate, key biomotion points emerged, culminating in a bowing motion when the vehicle came to a complete stop. In the non-yielding scenario, the vehicle maintained a consistent speed, with the biomotion points matching the speed.

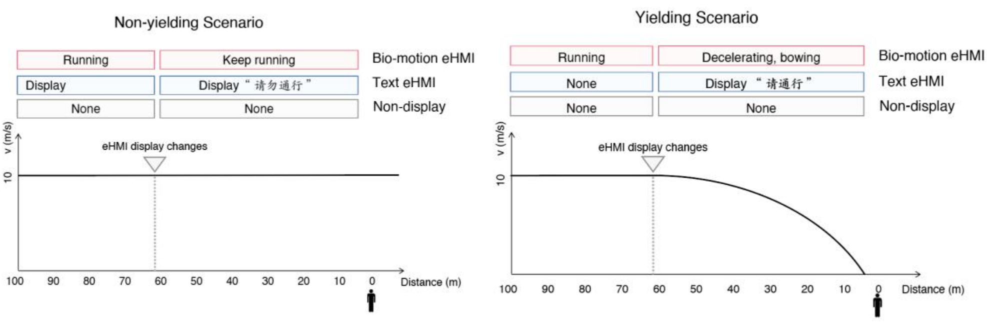

Figure 6. Functional Relationships of Vehicle Speed and Pedestrian Distance . (a) Non-Yielding and (b) Yielding Scenarios. **Vehicle Yielding Scenarios:** the vehicle moved at a uniform speed from a distance of 100 meters away from the pedestrian. At 61.25 meters, the vehicle conveyed interactive information and decelerated at 1.39m/s^2, finally stopping 5 meters in front of the pedestrian. **Vehicle Non-yielding Scenarios:** the vehicle signaled from a distance of 100 meters from the pedestrian and maintained a speed of 36 km/h throughout the scenario

This experiment employed a 3×3×2 mixed design, with age (5, 7, 9 years), type of External Human-Machine Interface (eHMI) (Bio-motion eHMI, Text eHMI, Non-display), and interaction scenario (vehicle yielding, vehicle not yielding) serving as independent variables. The dependent variables were the perceived safe crossing time (Clerq et al., 2019). Participants were required to watch video clips demonstrating various vehicle movements and complete corresponding tasks. They were asked to imagine themselves as pedestrians needing to cross the street to meet a friend on the other side. If they felt it was safe to cross, they were instructed to press and hold the 'space' button. As soon as they felt it was no longer safe to cross, they were to release the 'space' button. This process was repeated across three blocks (Bio-motion eHMI, Text eHMI, Non-display condition), using a Latin square design for counterbalancing. Each block consisted of six video clips (three instances of each of the two interaction scenarios) followed by two corresponding questions. In total, each participant viewed and responded to 18 video clips. Finally, participants were asked to select the eHMI type they found to be the easiest to comprehend from the three types. The entire experiment lasted approximately 30 minutes.

The Impact of Bio-motion eHMI on Street-Crossing Decisions of Chinese and German Individuals

Similar to the experimental materials and procedure in Experiment 4. Study 5 was a 3×2 within-subjects design. The independent variables were the types of external human-machine interface (Bio-motion eHMI, Chinese Text eHMI, and Non-display), and the interaction scenarios (vehicle yielding vs non-yielding). The dependent

variables was the perceived safety time (de Clercq et al., 2019). The experiment included a total of 30 videos, comprising five random interaction locations, two interaction scenarios, and three types of eHMIs. The eHMI types were counterbalanced using a Latin square design, with 10 videos randomly presented for each type.

Motion Speed Change Detection at Various Distance Among Chinese Adults

Study 6 examined the benefits of bio-motion eHMI during the perception phase when pedestrians interacts with AVs, particularly over extended distances (50m, 100m, 150m, 200m, 250m, 300m, and 350m).

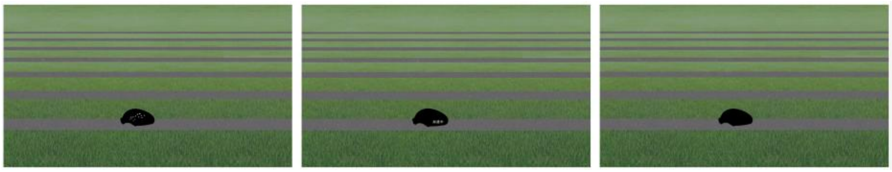

Figure 7. Perspective Background Material featuring Seven Roadways, Corresponding to Seven Levels of Perception Distances: 50m, 100m, 150m, 200m, 250m, 300m, and 350m. Experiment Materials Illustrating Different eHMIs: Bio-motion, Text, and Non-display condition. The experimental materials for this study are shown in the following figure. From left to right: Bio-motion eHMI, Text eHMI, and Non-display group. The different distance levels correspond to the roads in the figure. The calculation of element size was related to the distance and visual angle between the observer's eye and the object. By integrating the method of visual angle radian calculation, the real-world distance was derived from the distance under laboratory conditions. The formula for element size calculation was $S=2d*\tan(\alpha/2)$, where α was the visual angle ($\alpha=H1/S=H0/d$), S was the distance from the subject to the screen, d was the distance between the subject and the vehicle in real scenarios, H0 was the height in real scenarios, and H1 was the height of the light point on the screen. In the experiment, the distance S from the subject to the screen was 3.5m, and the height H0 of the light point in real scenarios was 0.8m. The height H of the light point was calculated based on different distances d. For example, when the distance was 50m, the height of the light point was 5.6cm, and when the distance was 200m, the height of the light point was 1.4cm. Research by Rettenmaier et al. (2020) found that the height of the text eHMI display content between 170mm (6.64 MOA) and 200mm (7.81 MOA) achieved good readability. Considering that the text eHMI could not cover the whole body of the vehicle like the light point, the height of the Chinese H0 was set to 1/3 of the height of the H0 light point (H0 Chinese=0.267m). To simulate the perception of vehicles and background information at different distances in real scenarios and produce a depth perception of the three-dimensional space, the background of the experimental material provided depth perception cues, including line perspective, air perspective, and texture gradient (the incremental change in the objective physical distribution density with the extension of the field of view).

The experiment implemented a 3 (eHMI type: Bio-motion eHMI, Text eHMI, Non-display) × 7 (perceived distance: 50m, 100m, 150m, 200m, 250m, 300m, 350m) × 4 (rate of acceleration or deceleration: $1m/s^2$, $1.5m/s^2$, $2m/s^2$, $2.5m/s^2$)

within-subjects design. The dependent variables were accuracy and reaction time in the judgment tasks. The experiment was divided into two parts: acceleration judgement task and deceleration judgement task, plus a start judgement task. After each task, the participants were asked about their certainty ('how certain are you' that the previous judgement was correct on a scale from 1=very uncertain, to 7=very certain). Questionnaires included measures of perceived safety and the SUS trust scale.

The tasks were presented with the following instructions: 'Next, you will watch a series of videos from the perspective of a pedestrian, where an autonomous vehicle will move on the road. The speed of the vehicle may change, such as accelerating, decelerating, or maintaining a constant speed. Please imagine you are a pedestrian. Your task is to accurately judge the change in the vehicle's motion. When you perceive a change in the vehicle's motion, immediately press the 'space' key on the keyboard.' The acceleration/deceleration judgement task followed the same procedure as the acceleration judgement task, comprising 21 blocks and 12 trials per block (8 deceleration trials, 4 constant speed distractor trials). Each trial lasted for 4 seconds, with the vehicle maintaining a constant speed between 0s-1s, then beginning to accelerate/decelerate evenly from 1s-4s. At the end of each block, participants were given a 1-minute break. Participants completed a total of 3×7×12×2=504 trials. The experiment lasted approximately 50 minutes.

References

1. Sucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis & Prevention*, *102*, 41–50. https://doi.org/10.1016/j.aap.2017.02.018
2. de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. (2019). External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. *Human Factors*, *61*(8), 1353–1370. https://doi.org/10.1177/0018720819836343
3. Eisma, Y. B., van Bergen, S., ter Brake, S. M., Hensen, M. T. T., Tempelaar, W. J., & de Winter, J. C. F. (2020). External Human–Machine Interfaces: The Effect of Display Location on Crossing Intentions and Eye Movements. *Information*, *11*(1), Article 1. https://doi.org/10.3390/info11010013
4. Wang, P., Motamedi, S., Qi, S., Zhou, X., Zhang, T., & Chan, C.-Y. (2021). Pedestrian interaction with automated vehicles at uncontrolled intersections. *Transportation Research Part F: Traffic Psychology and Behaviour*, *77*, 10–25. https://doi.org/10.1016/j.trf.2020.12.005
5. Carmona, J., Guindel, C., Garcia, F., & de la Escalera, A. (2021). eHMI: Review and Guidelines for Deployment on Autonomous Vehicles. *Sensors*, *21*(9), 2912. https://doi.org/10.3390/s21092912
6. Kooijman, L., Happee, R., & de Winter, J. (2019). How Do eHMIs Affect Pedestrians' Crossing Behavior? A Study Using a Head-Mounted Display Combined with a Motion Suit. *Information (Basel)*, *10*(12), 386.

https://doi.org/10.3390/info10120386

7. Barton, B. K., & Schwebel, D. C. (2006). The Roles of Age, Gender, Inhibitory Control, and Parental Supervision in Children's Pedestrian Safety. *Journal of Pediatric Psychology*, *32*(5), 517–526. https://doi.org/10.1093/jpepsy/jsm014
8. WH, O. (2018). Global status report on road safety 2018: Summary. *World Health Organization.*
9. Tiwari, R. R., Patel, S., Soju, A., & Trivedi, P. (2021). Road Use Pattern and Street Crossing Habits of Schoolchildren in India. Frontiers in Public Health, 9, 628147. https://doi.org/10.3389/fpubh.2021.628147
10. Hofstede, G. (1980). Motivation, leadership, and organization: Do American theories apply abroad? *Organizational Dynamics*, *9*(1), 42–63. https://doi.org/10.1016/0090-2616(80)90013-3
11. Aycan, Z. (2000). Cross-Cultural Industrial and Organizational Psychology: Contributions, Past Developments, and Future Directions. *Journal of Cross-Cultural Psychology*, *31*(1), 110–128. https://doi.org/10.1177/0022022100031001009
12. Yagil, D. (2000). Beliefs, motives and situational factors related to pedestrians' self-reported behavior at signal-controlled crossings. *Transportation Research Part F: Traffic Psychology and Behaviour*, *3*(1), 1–13. https://doi.org/10.1016/S1369-8478(00)00004-8
13. Chiswick, B. R., & Miller, P. W. (2003). The complementarity of language and other human capital: Immigrant earnings in Canada. *Economics of Education Review*, *22*(5), 469–480. https://doi.org/10.1016/S0272-7757(03)00037-2
14. Jones, D. G., & Endsley, M. R. (1996). Sources of situation awareness errors in aviation. *PubMed*, *67*(6), 507–512. https://pubmed.ncbi.nlm.nih.gov/8827130
15. DIN EN ISO 9241-303. (2011). Ergonomie der Mensch-System-Interaktion - Teil 303: Anforderungen an elektronische optische Anzeigen.
16. Dey, D., Martens, M., Wang, C., Ros, F., & Terken, J. (2018). Interface Concepts for Intent Communication from Autonomous Vehicles to Vulnerable Road Users. *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, *82–86*. https://doi.org/10.1145/3239092.3265946
17. Dey, D., De Zeeuw, C., Bruns, M., & Pfleging, B. (2021). Shape-Changing Interfaces as eHMIs: Exploring the Design Space of Zoomorphic Communication between Automated Vehicles and Pedestrians. *Shape-Changing Interfaces as eHMIs: Exploring the Design Space of Zoomorphic Communication Between Automated Vehicles and Pedestrians*, *137–141*. https://doi.org/10.1145/3473682.3480281
18. Kuderna, L. F. K., Ulirsch, J. C., Rashid, S., et al. (2024). Identification of constrained sequence elements across 239 primate genomes. *Nature, 625*, 735-742. https://doi.org/10.1038/s41586-023-06798-8
19. Darwin, C. (1872). *The expression of the emotions in man and animals*. John Murray. https://doi.org/10.1037/10001-000
20. De Waal, F. B. M. (1989). Food sharing and reciprocal obligations among

chimpanzees. *Journal of Human Evolution, 18*(5), 433–459. https://doi.org/10.1016/0047-2484(89)90074-2
21. Troje, N. F., Westhoff, C., & Lavrov, M. (2005). Person identification from biological motion: Effects of structural and kinematic cues. *Perception & Psychophysics*, *67*(4), 667–675. https://doi.org/10.3758/BF03193523
22. Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception & Psychophysics*, *14*(2), 201–211. https://doi.org/10.3758/BF03212378
23. Blake, R., & Shiffrar, M. (2007). Perception of Human Motion. *Annual Review of Psychology*, *58*(1), 47–73. https://doi.org/10.1146/annurev.psych.57.102904.190152
24. Tyrrell, R. A., Wood, J. M., Chaparro, A., Carberry, T. P., Chu, B.-S., & Marszalek, R. P. (2009). Seeing pedestrians at night: Visual clutter does not mask biological motion. *Accident Analysis & Prevention*, *41*(3), 506–512. https://doi.org/10.1016/j.aap.2009.02.001
25. Buzzell, G., Chubb, L., Safford, A. S., Thompson, J. C., & McDonald, C. G. (2013). Speed of Human Biological Form and Motion Processing. *PLoS ONE, 8*(7), e69396. https://doi.org/10.1371/journal.pone.0069396
26. Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2018). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology & Work, 21*(1), 69–85. https://doi.org/10.1007/s10111-018-0521-z
27. Faas, S. M., Kao, A. C., & Baumann, M. (2020). A Longitudinal Video Study on Communicating Status and Intent for Self-Driving Vehicle – Pedestrian Interaction. 14. https://doi.org/10.1145/3313831.3376484
28. Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., Fagerlönn, J., Fredriksson, R., Edgren, C., Krupenia, S., & Saluäär, D. (2017). Will There Be New Communication Needs When Introducing Automated Vehicles to the Urban Context? In N. A. Stanton, S. Landry, G. Di Bucchianico, & A. Vallicelli (Eds.), *Advances in Human Aspects of Transportation*, 485–497. Springer International Publishing. https://doi.org/10.1007/978-3-319-41682-3_41
29. Mahadevan, K., Somanath, S., & Sharlin, E. (2018). Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–12. https://doi.org/10.1145/3173574.3174003
30. Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272–282. https://doi.org/10.1016/j.apergo.2018.11.002
31. Simion, F., Regolin, L., & Bulf, H. (2008). A predisposition for biological motion in the newborn baby. *Proceedings of the National Academy of Sciences*, *105*(2), 809–813. https://doi.org/10.1073/pnas.0707021105
32. Booth, A. E., Pinto, J., & Bertenthal, B. I. (2002). Perception of the symmetrical

patterning of human gait by infants. *Developmental Psychology*, *38*(4), 554–563. https://doi.org/10.1037/0012-1649.38.4.554

33. Kuhlmeier, V. A., Troje, N. F., & Lee, V. (2010). Young Infants Detect the Direction of Biological Motion in Point-Light Displays: DETECTING THE DIRECTION OF BIOLOGICAL MOTION. *Infancy*, *15*(1), 83–93. https://doi.org/10.1111/j.1532-7078.2009.00003.x
34. Gilmore, G. C., Wenk, H. E., Naylor, L. A., & Stuve, T. A. (1992). Motion perception and aging. *Psychology and Aging*, *7*(4), 654–660. https://doi.org/10.1037/0882-7974.7.4.654
35. Norman, J. F., Todd, J. T., & Orban, G. A. (2004). Perception of Three-Dimensional Shape From Specular Highlights, Deformations of Shading, and Other Types of Visual Information. *Psychological Science*, *15*(8), 565–570. https://doi.org/10.1111/j.0956-7976.2004.00720.x
36. Sekuler, R., Hutman, L. P., & Owsley, C. J. (1980). Human Aging and Spatial Vision. *Science*, *209*(4462), 1255–1256. https://doi.org/10.1126/science.7403884
37. Pica, P., Jackson, S., Blake, R., & Troje, N. F. (2011). Comparing biological motion perception in two distinct human societies. *PloS One, 6*(12), e28391. https://doi.org/10.1371/journal.pone.0028391
38. Mather, G., & West, S. (1993). Recognition of Animal Locomotion from Dynamic Point-Light Displays. *Perception*, *22*(7), 759–766. https://doi.org/10.1068/p220759
39. Chang, D. H. F., & Troje, N. F. (2009). Acceleration carries the local inversion effect in biological motion perception. *Journal of Vision, 9*(1), 1–17. https://doi.org/10.1167/9.1.19
40. Thornton, I., Wootton, Z., & Pedmanson, P. (2014). Matching Biological Motion at Extreme Distances. *Journal of Vision*, *14*. https://doi.org/10.1167/14.3.13Thurman, S. M., & Grossman, E. D. (2008). Temporal "Bubbles" reveal key features for point-light biological motion perception. *Journal of Vision*, *8*(3), 28. https://doi.org/10.1167/8.3.28Tiwari, R. R., Patel, S., Soju, A., & Trivedi, P. (2021). Road Use Pattern and Street Crossing Habits of Schoolchildren in India. *Frontiers in Public Health*, *9*, 628147. https://doi.org/10.3389/fpubh.2021.628147
41. Ahlström, V., Blake, R., & Ahlström, U. (1997). Perception of Biological Motion. *Perception*, *26*(12), 1539–1548. https://doi.org/10.1068/p261539
42. Kremer, L., Klein Holkenborg, S. E. J., Reimert, I., Bolhuis, J. E., & Webb, L. E. (2020). The nuts and bolts of animal emotion. *Neuroscience & Biobehavioral Reviews*, *113*, 273–286. https://doi.org/10.1016/j.neubiorev.2020.01.028
43. Aureli, F., Cords, M., & Van Schaik, C. P. (2002). Conflict resolution following aggression in gregarious animals: A predictive framework. *Animal Behaviour*, *64*(3), 325–343. https://doi.org/10.1006/anbe.2002.3071
44. Hirai, M., & Hiraki, K. (2005). An event-related potentials study of biological motion perception in human infants. *Cognitive Brain Research*, *22*(2), 301–304. https://doi.org/10.1016/j.cogbrainres.2004.08.008
45. Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns'

preferential tracking of face-like stimuli and its subsequent decline. *Cognition*, *40*(1–2), 1–19. https://doi.org/10.1016/0010-0277(91)90045-6

46. Scofield, J., Hernandez-Reif, M., & Keith, A. B. (2009). Preschool Children's Multimodal Word Learning. *Journal of Cognition and Development*, *10*(4), 306–333. https://doi.org/10.1080/15248370903417662
47. Fawcett, C., & Tunçgenç, B. (2017). Infants' use of movement synchrony to infer social affiliation in others. *Journal of Experimental Child Psychology*, *160*, 127–136. https://doi.org/10.1016/j.jecp.2017.03.014
48. Troje, N. F., & Westhoff, C. (2006). The inversion effect in biological motion perception: evidence for a "life detector"?. *Current biology : CB, 16*(8), 821–824. https://doi.org/10.1016/j.cub.2006.03.022
49. Farah, M. J., Tanaka, J. W., & Drain, H. M. (1995). What causes the face inversion effect? *Journal of Experimental Psychology: Human Perception and Performance, 21*(3), 628–634. https://doi.org/10.1037/0096-1523.21.3.628
50. Goren, C. C., Sarty, M., & Wu, P. Y. K. (1975). Visual Following and Pattern Discrimination of Face-like Stimuli by Newborn Infants. *Pediatrics, 56*(4), 544–549. https://doi.org/10.1542/peds.56.4.544
51. McLeod, S. (2007). Jean Piaget's theory of cognitive development.
52. Rettenmaier, M., Schulze, J., & Bengler, K. (2020). How Much Space Is Required? Effect of Distance, Content, and Color on External Human–Machine Interface Size. *Information*, *11*(7), 346. https://doi.org/10.3390/info11070346
53. Tremoulet, P. D., & Feldman, J. (2000). Perception of Animacy from the Motion of a Single Object. Perception, 29(8), 943–951. https://doi.org/10.1068/p3101
54. Pennycuick, C. J. (1975). On the Running of the GNU (Connochaetes Taurinus) and other Animals. *Journal of Experimental Biology*, *63*(3), 775–799. https://doi.org/10.1242/jeb.63.3.775
55. Atkinson, R.C., & Juola, J.F. (1973). Factors influencing speed and accuracy of word recognition. In S.Kornblum (Ed.), *Attention and Performance IV*. New York: Academic Press.
56. Wickelgren, W. A. (1973). The long and the short of memory. *Psychological Bulletin, 80*(6), 425–438. https://doi.org/10.1037/h0035255
57. Bazilinskyy, P., Dodou, D., & De Winter, J. (2019). Survey on eHMI concepts: The effect of text, color, and perspective. *Transportation Research Part F-traffic Psychology and Behaviour*, *67*, 175–194. https://doi.org/10.1016/j.trf.2019.10.013
58. Hudson, P., Corr, S. A., Payne-Davis, R. C., Clancy, S. N., Lane, E., & Wilson, A. M. (2011). Functional anatomy of the cheetah (Acinonyx jubatus) forelimb. Journal of Anatomy, 218(4), 375–385. https://doi.org/10.1111/j.1469-7580.2011.01344.x
59. Hildebrand, M. (1959). Motions of the Running Cheetah and Horse. *Journal of Mammalogy*, *40*(4), 481. https://doi.org/10.2307/1376265
60. Fischer, M. S., & Blickhan, R. (2006). The tri-segmented limbs of therian mammals: Kinematics, dynamics, and self-stabilization—a review. *Journal of Experimental Zoology Part A: Comparative Experimental Biology*, *305A*(11),

935–952. https://doi.org/10.1002/jez.a.333

61. Lilje, K. E., Tardieu, C., & Fischer, M. S. (2003). Scaling of long bones in ruminants with respect to the scapula. *Journal of Zoological Systematics and Evolutionary Research*, *41*(2), 118–126. https://doi.org/10.1046/j.1439-0469.2003.00207.x
62. Bartneck, C., Kulic, D., Croft, E. A., & Zoghbi, S. (2008). Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. *International Journal of Social Robotics*, *1*(1), 71–81. https://doi.org/10.1007/s12369-008-0001-3
63. Jian, J.-Y., Bisantz, A. M., & Drury, C. G. (2000). Foundations for an Empirically Determined Scale of Trust in Automated Systems. *International Journal of Cognitive Ergonomics*, *4*(1), 53–71. https://doi.org/10.1207/S15327566IJCE0401_04
64. Cao, J., Li, L., Zhang, J., Zhang, L., Wang, Y., & Wang, J. (2021). The development and validation of the perceived safety of intelligent connected vehicles scale. *Accident Analysis & Prevention*, *154*, 106092. https://doi.org/10.1016/j.aap.2021.106092
65. Laugwitz, B., Held, T., & Schrepp, M. (2008). Construction and evaluation of a user experience questionnaire. In *Lecture Notes in Computer Science*, 63–76. https://doi.org/10.1007/978-3-540-89350-9_6